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Title: Neutrinos, antineutrinos and the question: Why are we here?

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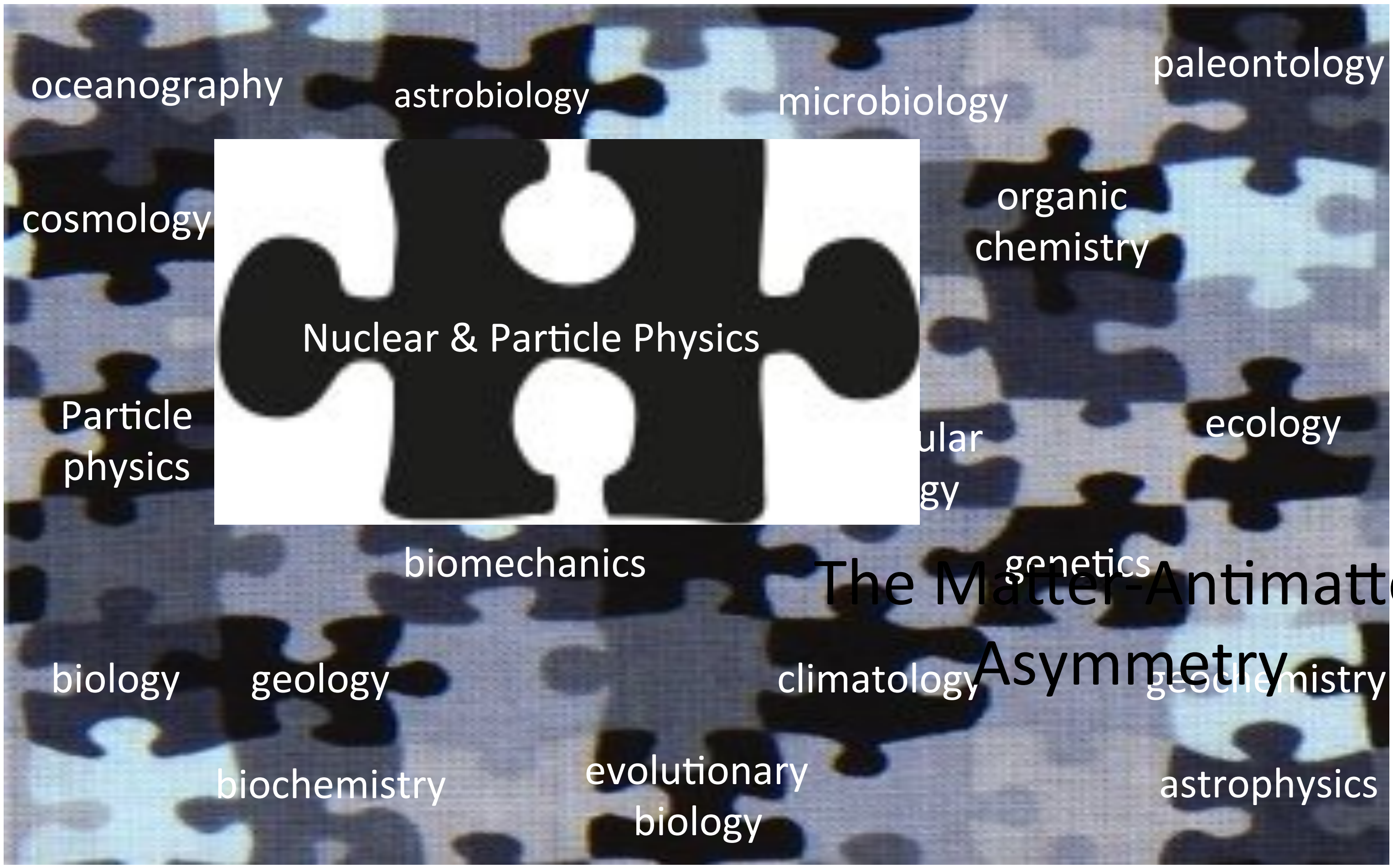
Neutrinos, Anti-neutrinos and the Question: Why are we here?

Steve Elliott

Los Alamos National Laboratory

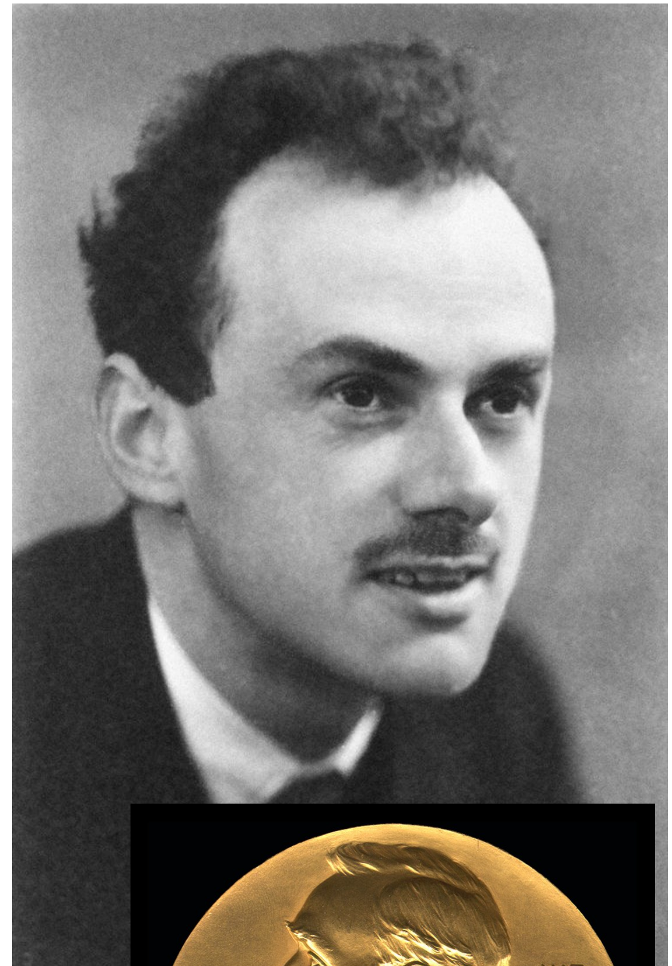
The science of "how we came to be"



The Matter-Antimatter Asymmetry

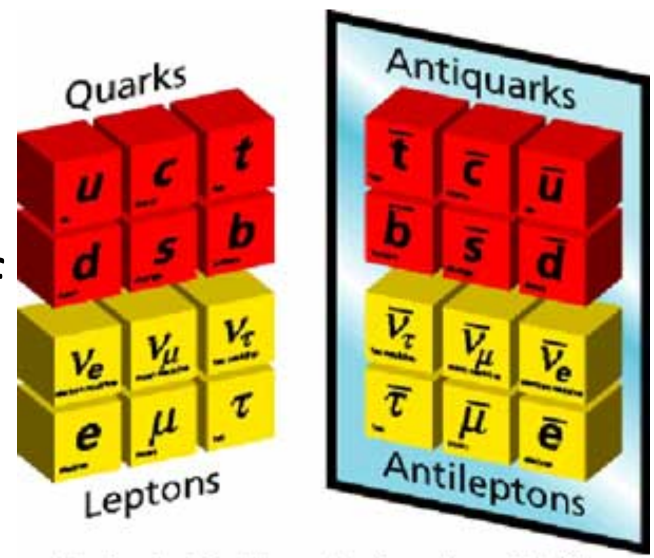
Paul Dirac

- Nobel prize winner for formulating quantum mechanics in a way consistent with Einstein's theory of relativity.
- This theory predicted anti-particles, which were discovered soon thereafter.



Particles and Antiparticles

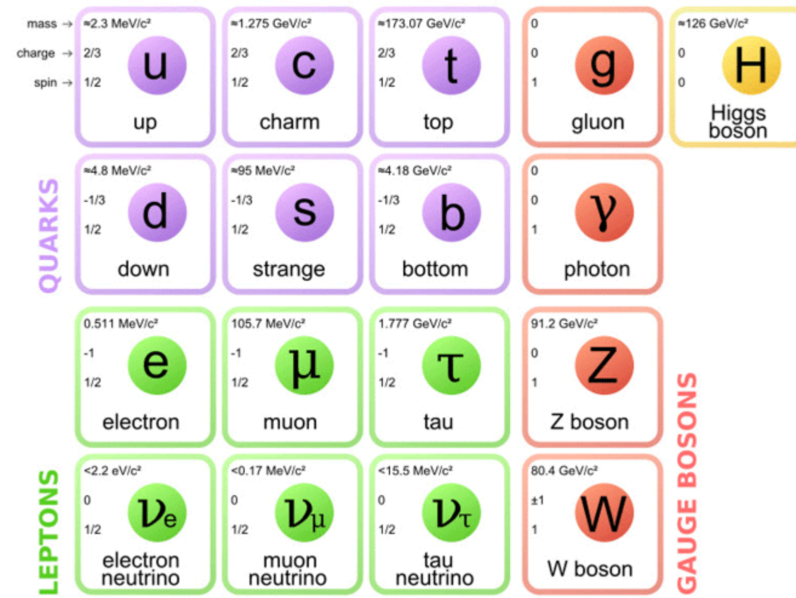
- Particle, antiparticle
  - Same mass, opposite charge
  - Will annihilate into energy (photons)
- Some examples
  - Electron, positron
  - Neutron, antineutron
- The photon (light) is an example of a particle that is its own antiparticle.



The Standard Model contains 3 neutrinos of definite flavor, and a set of corresponding anti-particles.

How Do Neutrinos Fit In

- Neutrinos are electrically neutral particles that only experience the weak force.
  - Strong force: holds nuclei together
  - Weak force: responsible for the interactions that power the Sun
  - Electricity & Magnetism: force between charged particles.
  - Gravity: force between particles with mass. A very weak force
- It is not known if neutrinos are their own antiparticles.



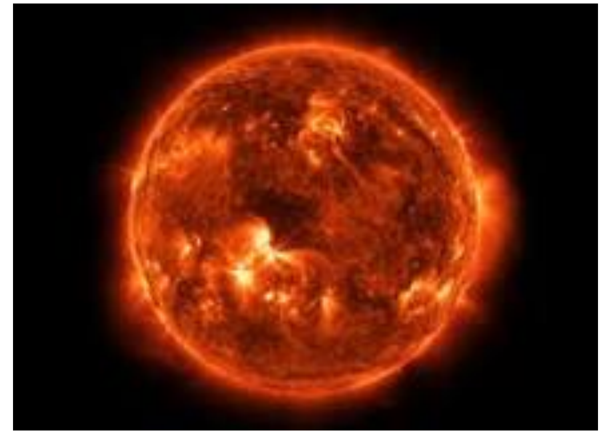
Neutrinos and Electrons

- Neutrinos are close cousins to electrons.
  - They are produced together in beta decay.
    - Beta decay is the process where a neutron decays producing a proton, electron and antineutrino.
  - Both particles experience the weak force.
  - Neither experiences the strong force.
- The electron is distinct from its antiparticle.
  - The positron: the two have opposite electrical charges.
- Hence it might seem reasonable that the neutrino would be similar and have a distinct antiparticle.

But Neutrinos and Electrons are Different in Many Ways

- Electrons have electrical charge and neutrinos are neutral.
- Neutrinos have a much smaller mass.
  - Theory has a way to explain this great difference in mass, with the result is that neutrinos are their own antiparticle.

So, are Neutrinos their own Antiparticles? Why Don't We Know the Answer?



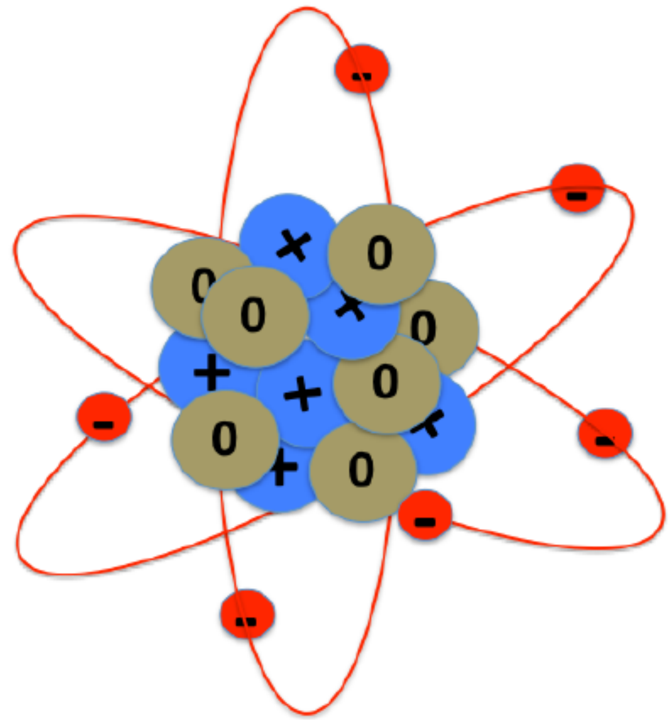
- Because neutrinos only interact weakly, they are very hard to study. They just don't do much.
- The Sun emits a LOT of neutrinos.
  - 60 billion of them pass through your thumbnail every second.
  - Once every 30 years or so, one of those neutrinos will interact in your thumb.
- For every 100 billion neutrinos that cross the Earth, only 1 interacts.

Ettore Majorana

- Disappeared at sea in 1938.
- Showed that neutrinos could be their own antiparticles and that would not contradict anything we knew about radioactive decay (1937).
- Our experiment, The MAJORANA Project, was named in his honor.

Baryons and Leptons some unfortunate jargon

- Baryon: protons, neutrons
- Lepton: electrons, neutrinos
- Empirically, these quantities are conserved in all reactions we have observed to date.
  - The total number of baryons or leptons will be constant in a reaction.



Baryons, Leptons

- Protons and neutrons have B=1. Antiprotons and antineutrons have B=-1. Both have L=0.
- Electrons and neutrinos have L=1. Both have B=0.
- The sum of B or L before and after an interaction should be the same.

Beta Decay, Neutrino Capture: Both Conserve B & L.

$$n \Rightarrow p + e^- + \bar{\nu}_e$$

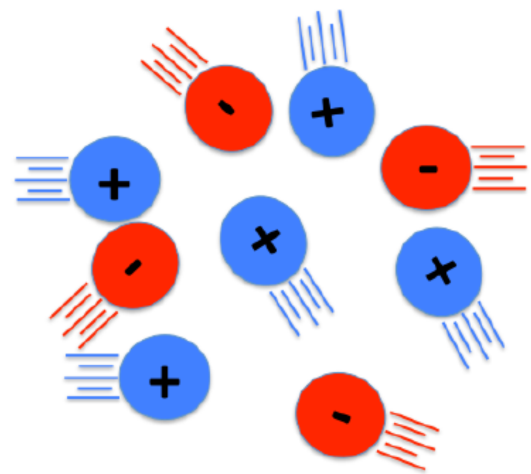
1	1	0	0	Baryon number, 1=1
0	0	1	-1	Lepton number, 0=0

$$\nu_e + n \Rightarrow p + e^-$$

0	1	1	0	Baryon number, 1=1
1	0	0	1	Lepton number, 1=1

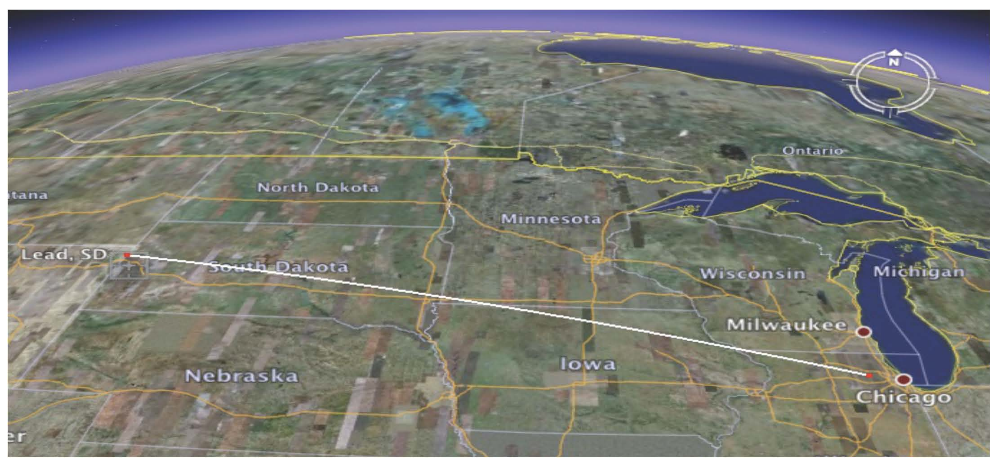
The Big Bang

- The Big bang produced equal numbers of particles and antiparticles. (i.e. baryons and leptons)
- But 13.8 billion years later, the universe is only particles.
- Somehow, 1 in a billion protons did not annihilate with antiprotons.
- Why did some fraction of the matter survive?
  - The matter/antimatter asymmetry problem



Baryons, Leptons and the Big Bang

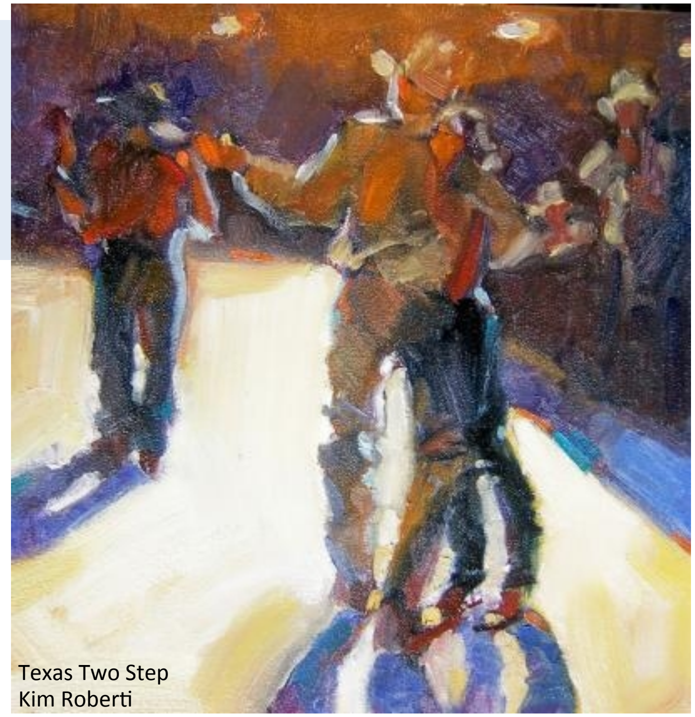
- For this asymmetry to arise requires that baryon number not be conserved absolutely. Just a little bit of non-conservation is required.
  - Or equivalently, lepton number must not be conserved.
  - We started with an equal number of baryons and antibaryons, but didn't end up with that.
- There must also be some small difference between particles and antiparticles and their decay.
  - Without this condition, any process that created an excess of baryons would destroy them in equal numbers.
  - The DUNE project is designed to study this aspect of the question.



A Two-Step Process

$$n \Rightarrow p + e^- + \bar{\nu}_e$$

$$\nu_e + n \Rightarrow p + e^-$$



Texas Two Step
Kim Roberti

Can the emitted neutrino in the first reaction induce the second reaction?

– If so, then there is no difference between neutrino and anti-neutrino. Hence a search for this process is a test of whether neutrinos are their own antiparticle.

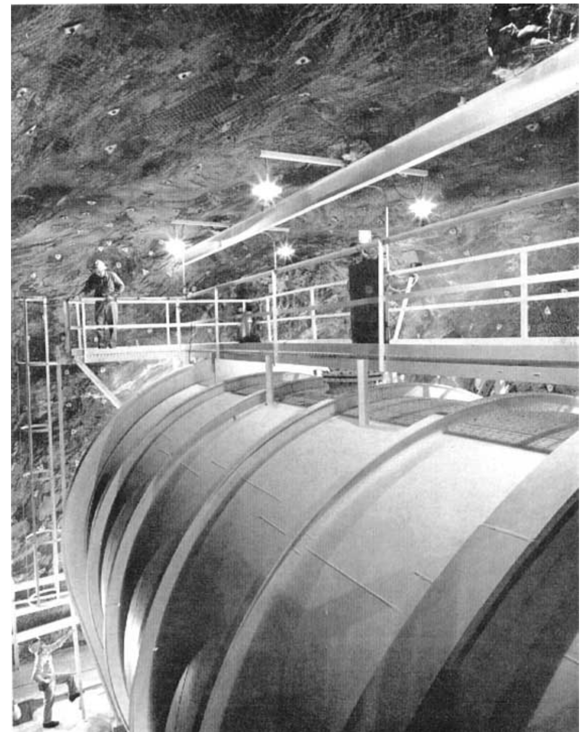
Ray Davis and the Chlorine Experiment at a Reactor

- Ray looked for this **two-step process** but didn't find it (1955).
- Reactors emit anti-neutrinos because of beta decay. Step One.
- His detector, made of Chlorine would only see neutrinos. Step Two.
- Did this imply that neutrinos and anti-neutrinos are different?
- No. This result was not very sensitive.
  - The probability of an interaction is very very small.

$$n \Rightarrow p + e^{-} + \bar{\nu}_e$$

$$\nu_e + n \Rightarrow p + e^{-}$$

Ray Davis at Homestake 50 years ago



- Ray brought this technology to Homestake to look for neutrinos (not anti-neutrinos) from the Sun.
- The Sun emits neutrinos, not anti-neutrinos.
- The Chlorine experiment used 600 tons of cleaning fluid and observed about 15 interactions per month.
- This was a factor of about 3 less than expected.
- This difference between the measured and expected rates is a result of neutrinos having mass.
  - Topic for another Neutrino Day talk
- This experiment at Homestake was the first indication that neutrinos have mass.
- Ray won the Nobel Prize for this work.

Maria Goeppert-Mayer

- Nobel prize winner for proposing the nuclear shell model.
- Did first estimate of two neutrino ββ rate (1935).

$$2n \Rightarrow 2p + 2e^{-} + 2\overline{\nu}_e$$

This reaction conserves L.

What is two-neutrino ββ?

$$2n \Rightarrow 2p + 2e^{-} + 2\overline{\nu}_e$$

- Two neutrons decaying simultaneously within the same nucleus.
- Some nuclei stable against a lone neutron decaying, allow two neutrons to simultaneously decay.

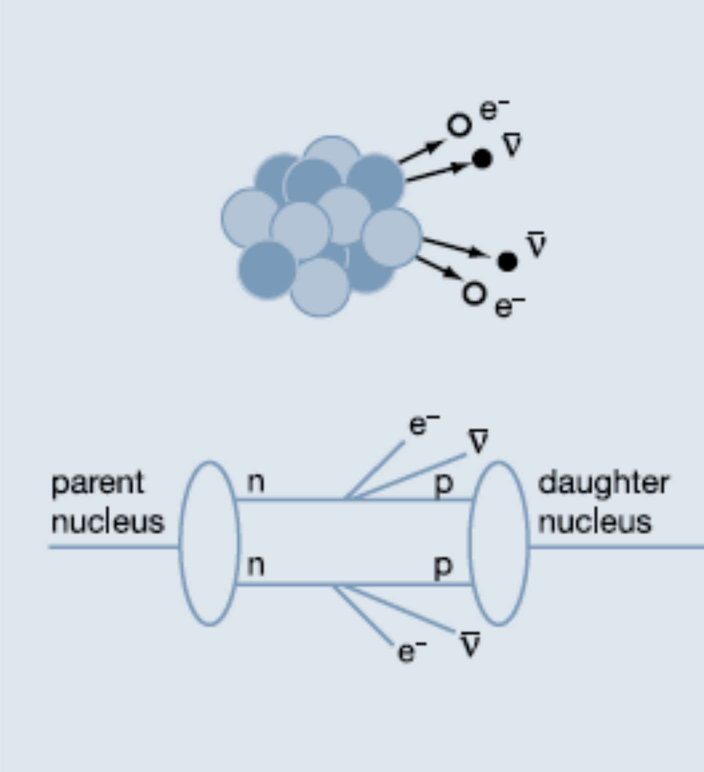


Fig. from Deep Science

Lets revisit the two step process

$$2n \Rightarrow 2p + 2e^- + 2\bar{\nu}_e$$

This reaction, two coincident neutron decays, conserves L.

$$n \Rightarrow p + e^- + \bar{\nu}_e$$

$$\nu_e + n \Rightarrow p + e^-$$

This reaction, a neutrino exchange between 2 neutrons, does not.

$$2n \Rightarrow 2p + 2e^-$$

0 0 2 Lepton number violated by 2

Wendell Furry

- Fought a lengthy battle with the House Unamerican Activities Committee.
- He recognized that this two-step process would be possible within a nucleus if neutrinos are their own anti-particles (1939).
- Experimental efforts to observe the decay began with Ed Fireman in 1948.

What is zero neutrino ββ?

$$n \Rightarrow p + e^- + \bar{\nu}_e \qquad \nu_e + n \Rightarrow p + e^-$$

- Both steps happen within a nucleus.
- The neutrino is exchanged between two neutrons within the nucleus. It never leaves the nucleus.
- Hence "zero neutrino".
- Neutrinos must have mass, also.
  - But Ray already showed that.

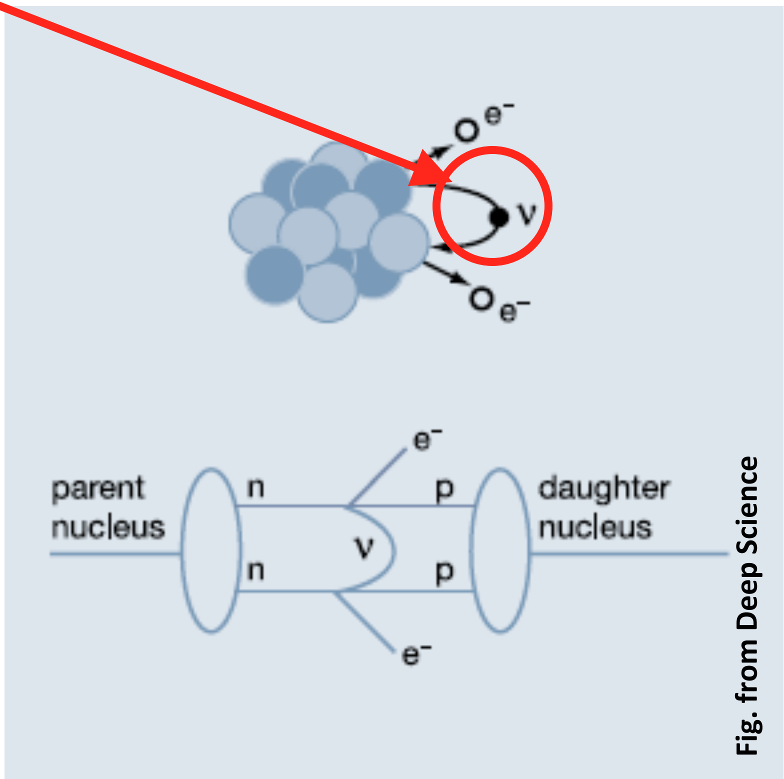


Fig. from Deep Science

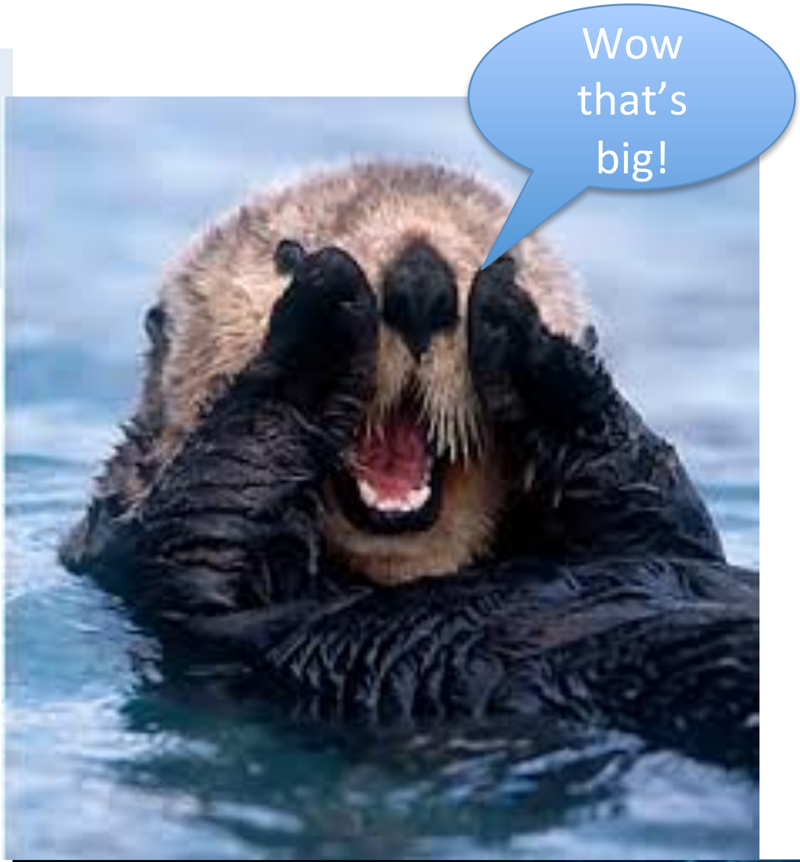
Look for Transition in a Nucleus

To see $\beta\beta$ we need lots of atoms and very low background. First, lets talk atom count.

- We are looking for a very rare decay.
  - Half-life greater than 10^{25} years.
  - This a billion-million times the age of the Universe, which is 10^{10} years.
  - You would have to watch one atom for a time equal to a ten-trillion-trillion years to see it decay.
  - Or you could watch a lot of atoms for one year.
- One gather a lot of nuclei together.
  - Ge is a metal
  - 2 pounds is about the size of your fist.
  - 2 pounds of Ge, has about 15 **moles** of atoms.

Avagradro’s Number

- The number of atoms in a **mole**. (not the animal, the number)
  - 6.02×10^{23}
- There is ~1 mole of thumb-end-joint sized volumes of water in the pacific ocean.
- There is about 1 mole of molecules in 1¼ tablespoons of water.
- Mole Day: This year’s theme is: May the moles be with you. Celebrated from 6:02 am to 6:02 pm on Oct. 23.



$\beta\beta$ History: The background problem

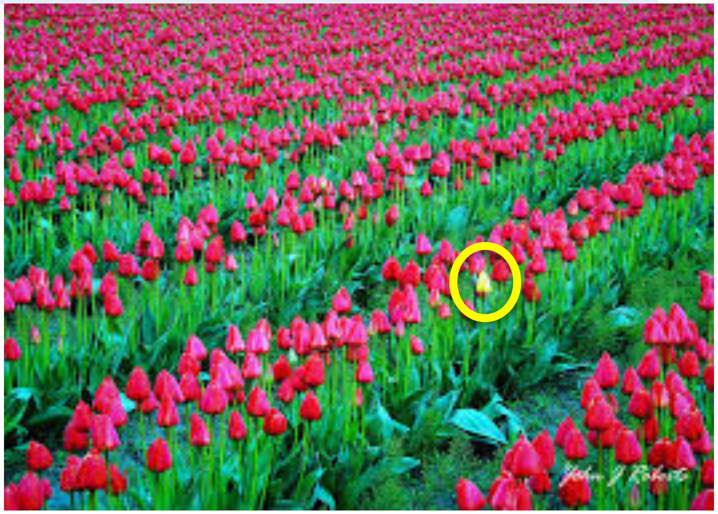
- $\beta\beta(2\nu)$ rate first calculated by Maria Goeppert-Mayer in 1935.
- First observed directly in 1987 (Mike Moe and collaborators => Bonner Prize).
- Why so long? **Background!** Other radioactivity hid the signal.

$$\tau_{1/2}(\mathrm{U, Th}) \sim T_{\mathrm{universe}}$$
$$\tau_{1/2}(\beta\beta(2\nu)) \sim 10^{10}\, T_{\mathrm{universe}}$$

- Those 50 years were spent doing the hard work of understanding where background came from and how to eliminate it.

Background: One of these things is not like the others.

- We must watch a lot of atoms.
- Still we want to see just a few events during a long viewing.
  - The expected signal is about 1 decay per year in a ton of detector.
  - In a typical adult, there are about 4500 radioactive decays per second!
- If anything else is happening in the detector it will hide those few events.
  - We need to pluck all the red flowers in the field to more easily find the yellow one.
- Technically this background problem is very difficult to solve.



Background Reduction Strategy

- Choose clean materials or purify materials.
  - Typical materials contain about 1 part/million U or Th.
  - We require about a million times better.
- Construct a shield to protect detectors.
  - Protects the experiment from the ambient radioactivity in the lab.
  - Construct it cleanly.
  - Clean room, detailed cleaning procedures.
- Reduce Radon.
- Go deep underground.
  - Avoid cosmic rays.
- Data analysis to look for key events.

Examples of things too radioactive for the experiment

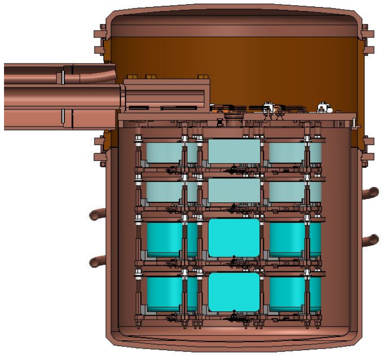
- Metals
  - We purify our own Cu. Produce and keep it below ground.
- Ceramics
  - Avoid or use very small quantities.
- Plastics
  - Developed a pure plastic with a vendor.
- Machining lubricants
  - Listen to machinists complain.
- Most cleaning supplies
  - Purchase expensive, highly purified acids.
- Air
  - Purge critical volumes with our own purified nitrogen gas.

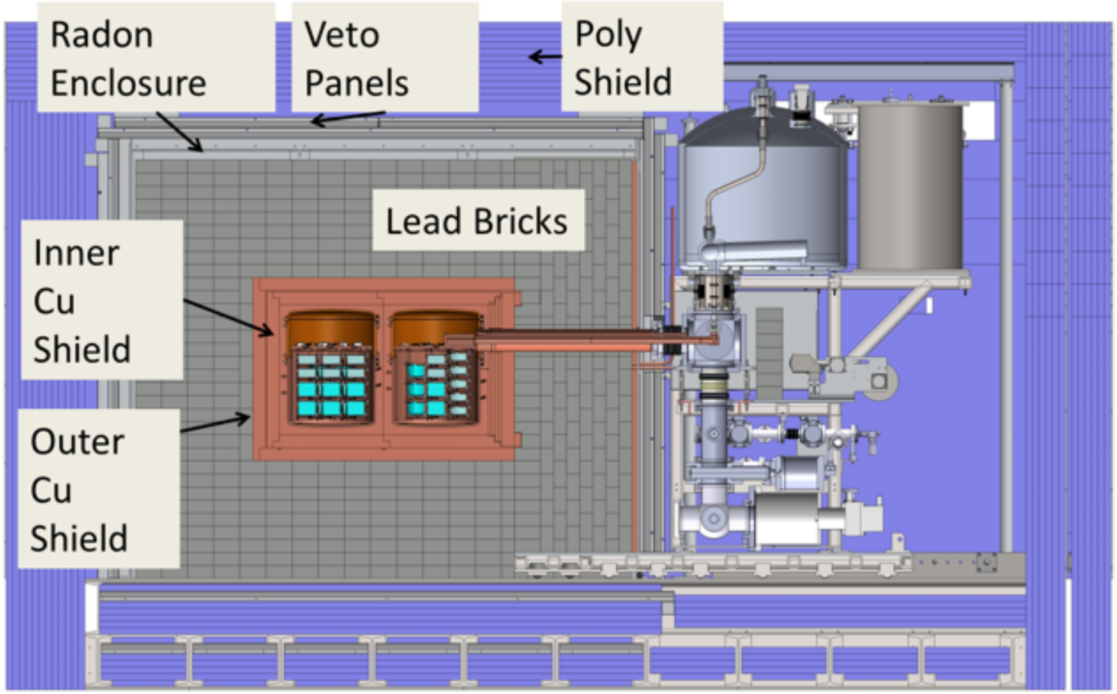
The MAJORANA COLLABORATION

Black Hills State University
Duke UNIVERSITY
ITEP
Joint Institute for Nuclear Research
BERKELEY LAB
Los Alamos NATIONAL LABORATORY
OAK RIDGE NATIONAL LABORATORY
TUNL
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
UNIVERSITY OF SOUTH CAROLINA
TENNESSEE TECH UNIVERSITY
M
THE UNIVERSITY of TENNESSEE
OSAKA UNIVERSITY
Pacific Northwest NATIONAL LABORATORY
W
UNIVERSITY OF SOUTH DAKOTA

The MAJORANA DEMONSTRATOR OVERVIEW

- Detectors fabricated from Ge, one of the elements that might double beta decay.
- Contained within a vacuum cryostat.
- Enclosed inside a large shield made of lead, copper and plastic.
- Located 4850’ underground at the Sanford Underground Research Facility.





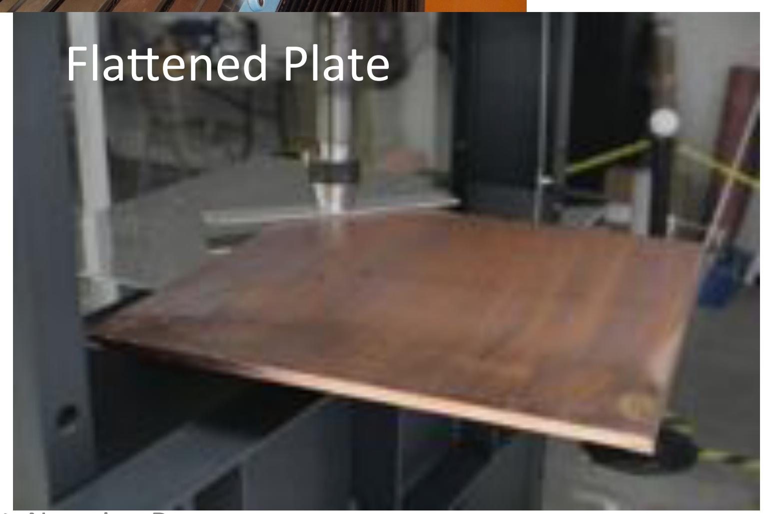
Electroforming: Obtaining Clean Cu

- **Electroform copper underground at SURF.**
- **Machine copper underground.**
- **Keep copper underground.**

Underground eForming Facility

Copper ready to cut

eForming baths

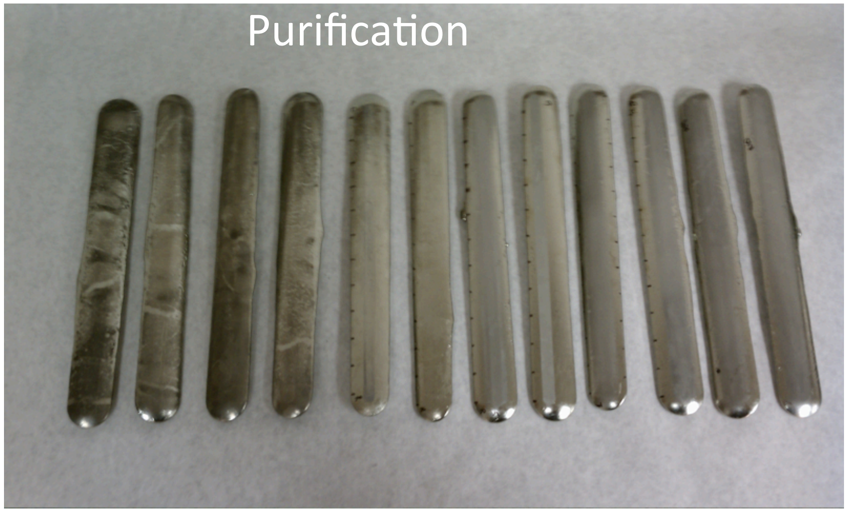


Flattened Plate

Electroformed Parts Stored in Nitrogen Underground.

Copper activates above ground due to cosmic rays.
Careful storage prevents Radon from contaminating surface.

Enriched Ge



Start with pure enriched Ge. Growing crystals to make detectors is an effective purification step. Results in almost no internal contaminants.

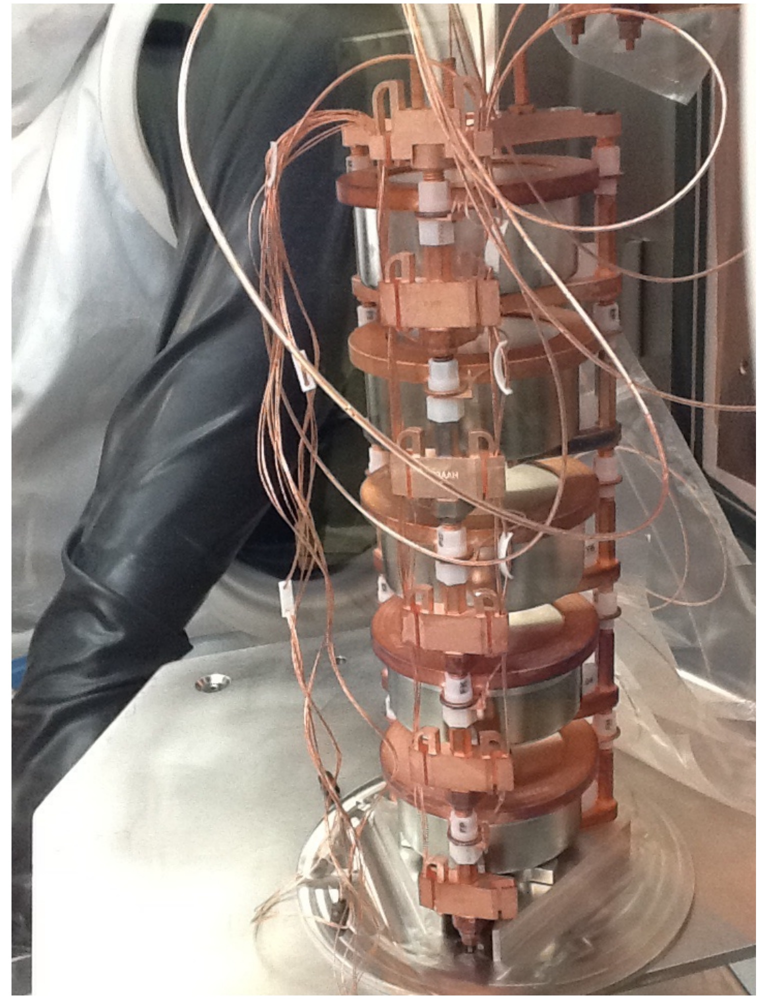
Assembled Detector Unit and String from specially selected ultra-clean materials

Electroformed Copper

Teflon

Small coaxial cable

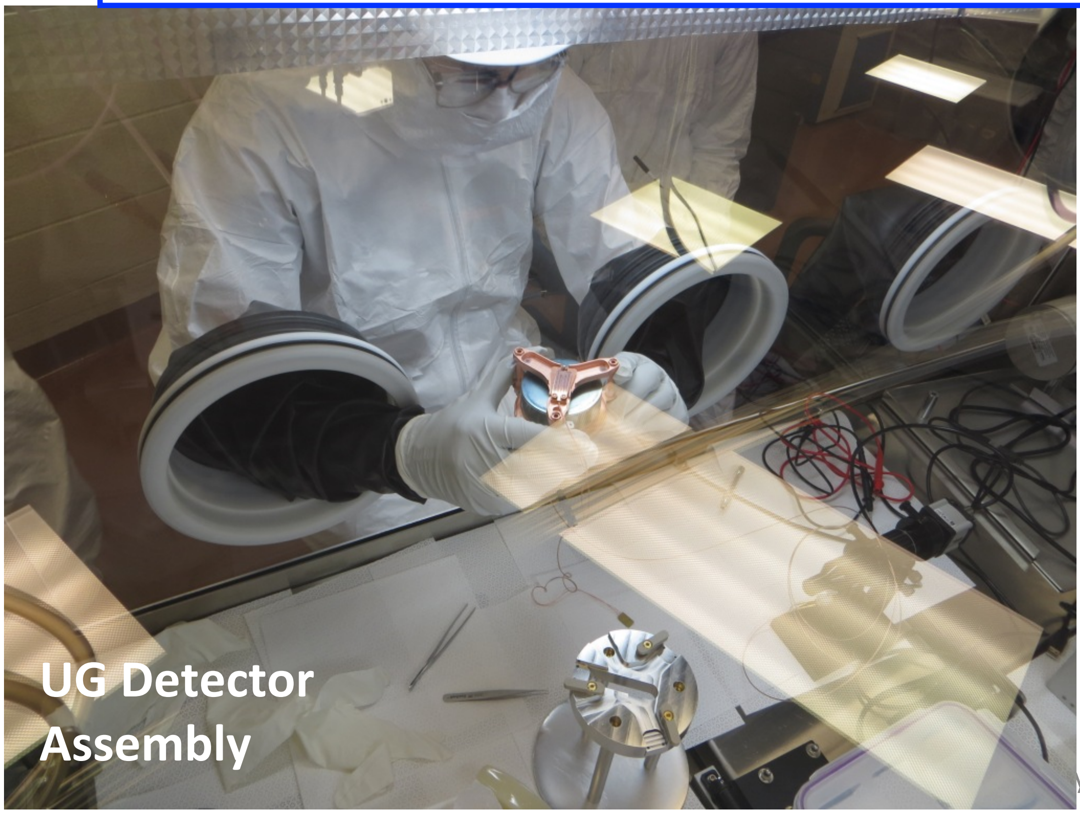
Front-End Electronics



String Assembly

Keep it all clean during assembly

- **All detector related assembly performed in nitrogen purged gloveboxes.**
- **Reduces oxygen and humidity: bad for detectors.**
- **Reduces Radon and dust: which are radioactive.**



UG Detector Assembly

35 Enriched detectors at SURF (29.65 kg, 87% ^{76}Ge).

33 modified natural-detectors in hand (20 kg).

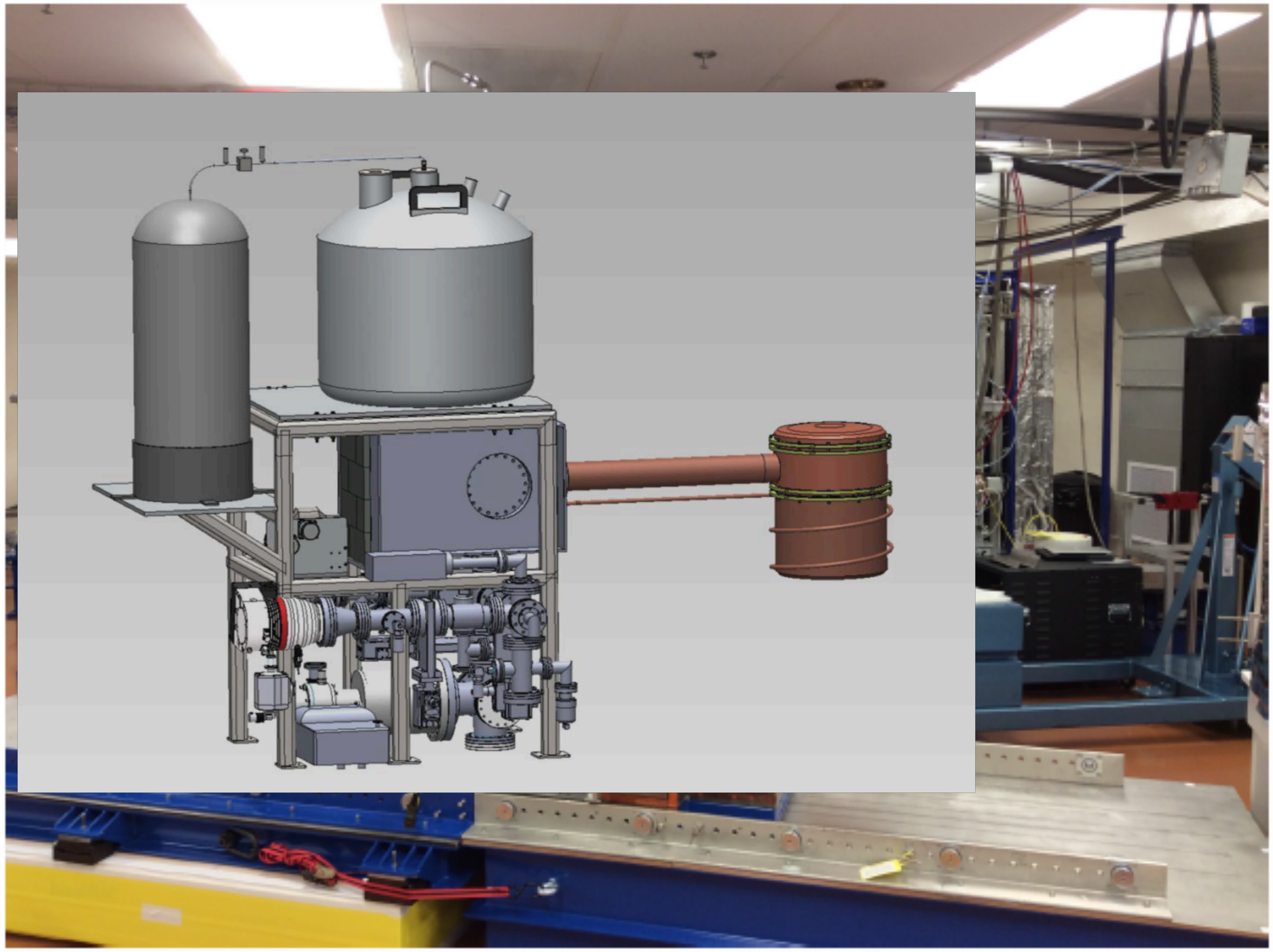
The Cryostat is also assembled in glove box


Photo: M. Kapust

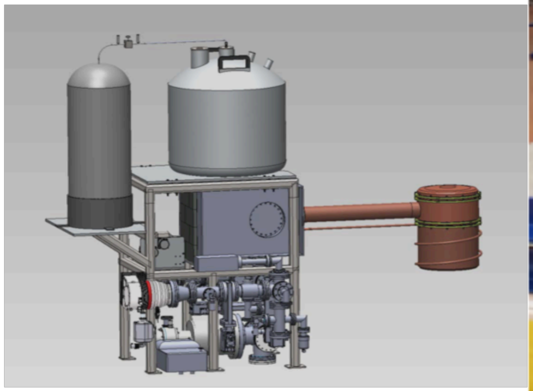
This pictured cryostat with enriched detectors is now installed inside the shield.

Modules Assembled in Clean Room

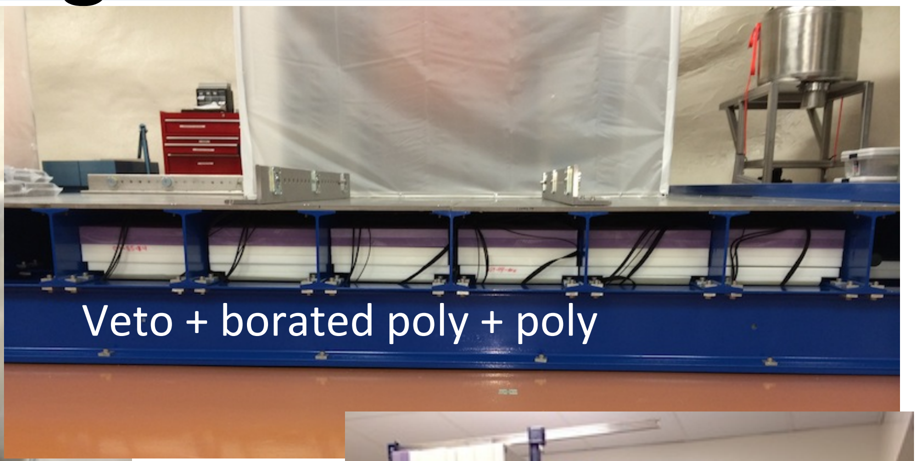
A Module is:
- **Cryostat**
- **Thermosyphon,**
- **Vacuum**
- **Shield Section**
- **All resting on a movable bearing table**

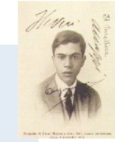


Modules Assembled in Clean Room

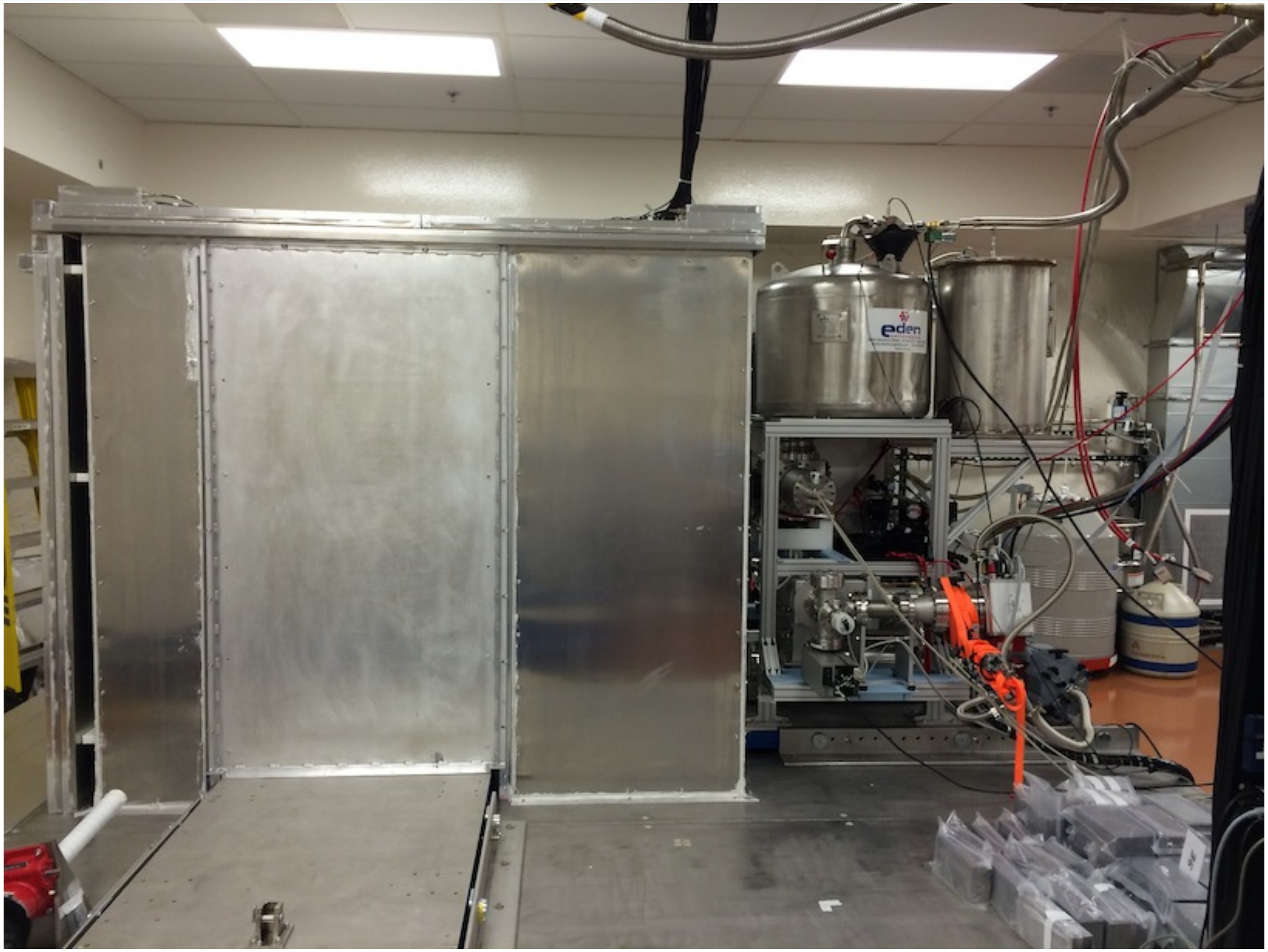


The Shield Blocks External Radiation. Some Photos During Construction.

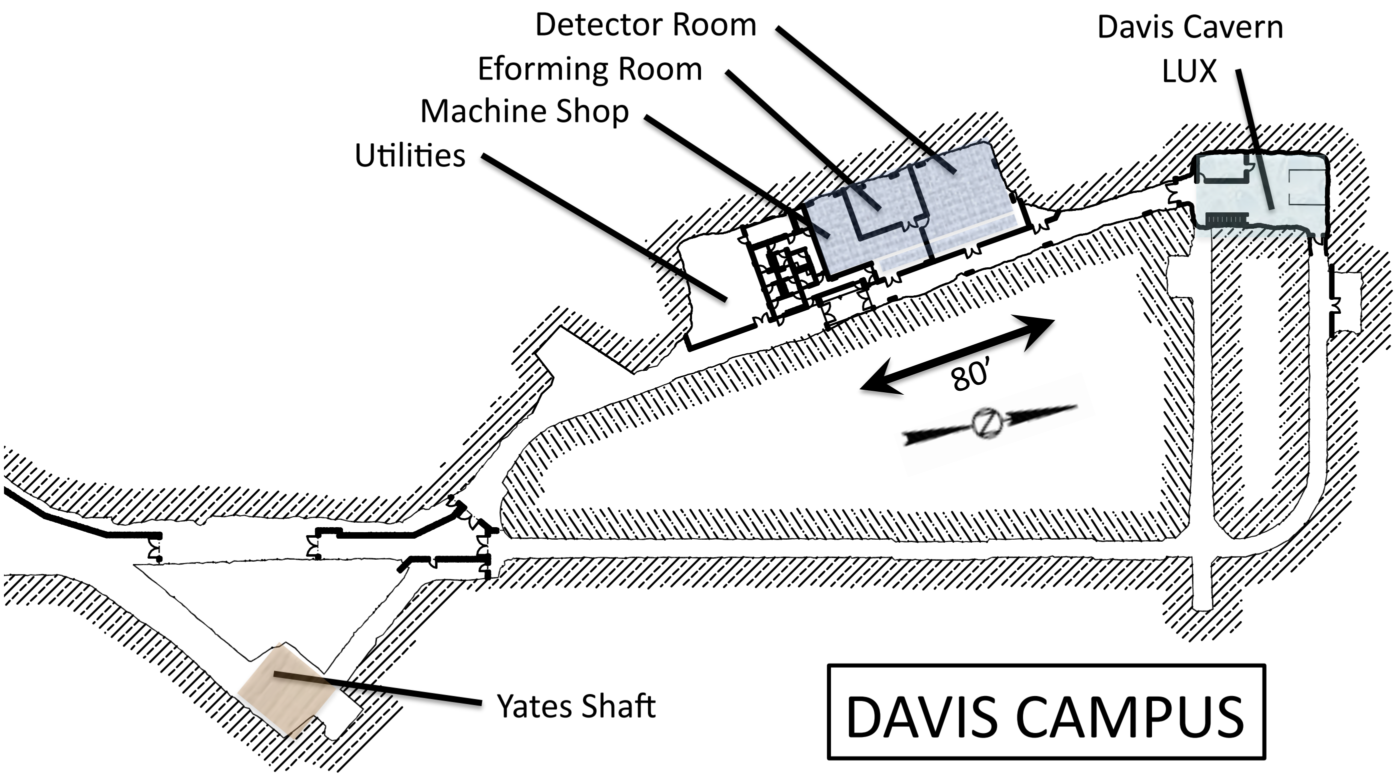




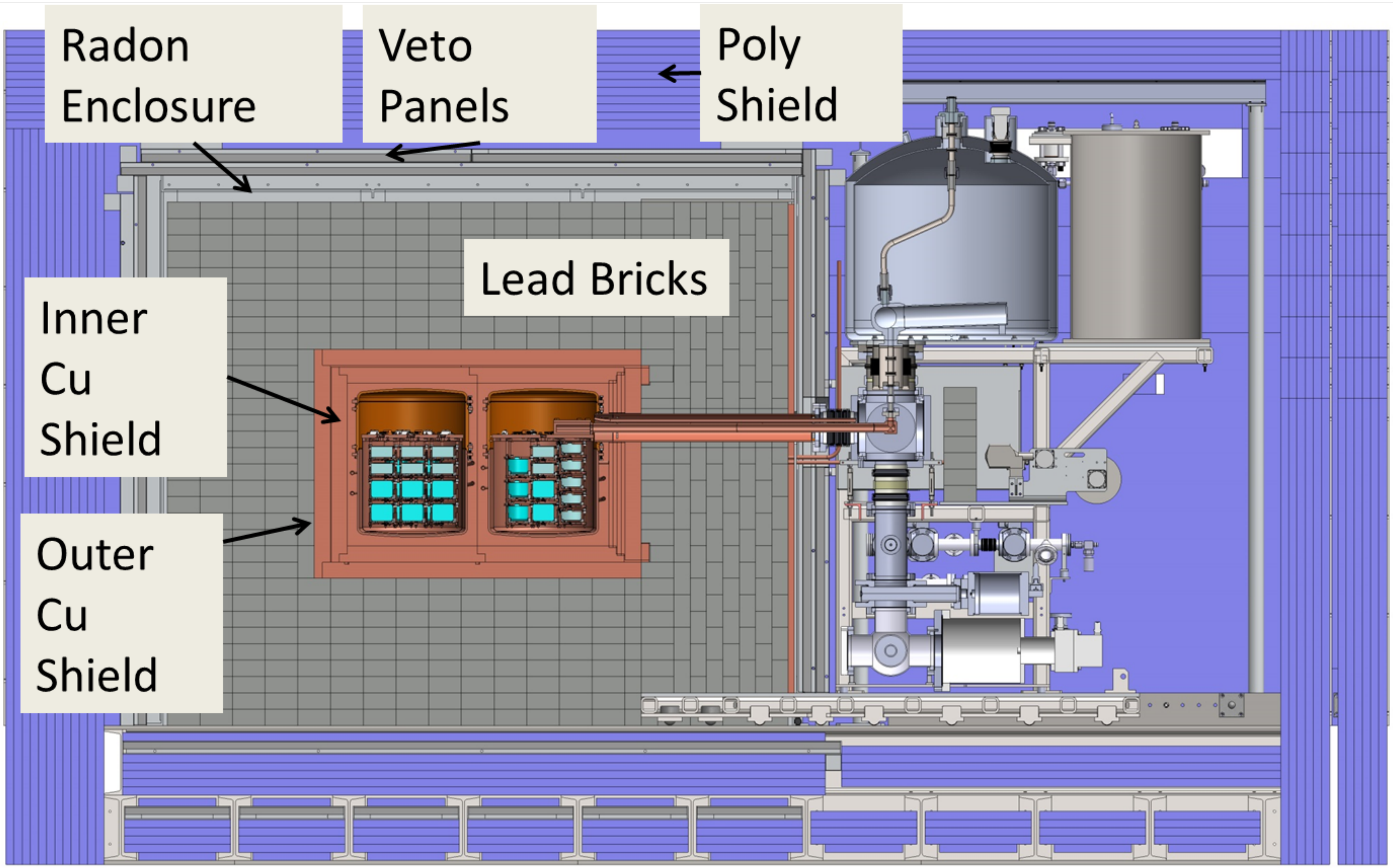
Module Installed in Shield



Put Experiment in Underground Laboratory to Avoid Cosmic Rays



Apparatus Overview



MAJORANA Summary

- First module is now operating.

- Second module is on-schedule to begin operation by year’s end.

The MAJORANA Collaboration

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